ROOT MORPHOLOGY OF DROUGHT RESISTANCE IN COTTON

(*GOSSYPIUM HIRSUTUM* L.)

A Thesis

by

ELVIRA SARI DEWI

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2009

Major Subject: Agronomy

ROOT MORPHOLOGY OF DROUGHT RESISTANCE IN COTTON

(*GOSSYPIUM HIRSUTUM* L.)

A Thesis

by

ELVIRA SARI DEWI

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Approved by:

Chair of Committee,	Harry Cralle
Committee Members,	C. Wayne Smith
	J. Tom Cothren
Head of Department,	David D. Baltensperger

December 2009

Major Subject: Agronomy

ABSTRACT

Root Morphology of Drought Resistance in Cotton (*Gossypium hirsutum* L.).

(December 2009)

Elvira Sari Dewi, B.S., Syiah Kuala University, Indonesia

Chair of Advisory Committee: Dr. Harry Cralle

A combination of root morphology and plant physiology with drought/or salt tolerance should affect drought resistance in cotton (*Gossypium hirsutum* L.). This experiment was developed to evaluate early vegetative and seedling growth of cotton from the unselected parents with two selected populations of M-8844-0100, DPL 50, and TAM 94L-25 across two cycles for seedling drought. Three genotypes from three generations of selection were grown in tubes to evaluate early growth and in containers to evaluate seedlings for drought resistance in a greenhouse at College Station, TX in 2008 and 2009. The experiment during the winter months of 2008 resulted in shorter tap root length, fewer lateral roots, and lower fresh and dry weight for total root, lateral roots, and shoots. The drought selections in these genotypes affected the tap root fresh weight, and the number and weight of lateral roots. TAM 94L-25 averaged higher tap root fresh and dry weight, lateral root fresh weight and shoot fresh weight. DPL 50 exhibited greater weight of lateral roots and shoot fresh weight. No difference was found in percent wilting across generations for drought at 75% apparent wilting and recovery at 90% apparent wilting.

To my parents

ACKNOWLEDGEMENTS

I would like to thank Dr. Harry Cralle for being a valuable mentor and role model. He was always available for consultation on issues related to my project and my academics. Sincere thanks are extended to Dr. Wayne Smith, who shared his expertise and guided my research. Many thank to Dr. J. T. Cothren for his advice and support throughout the course of this research.

Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience. I also want to extend my gratitude to the Fulbright Foundation for the opportunity to enrich my knowledge and experience during my stay in the U.S.

Finally, thanks to my mother and father for their encouragement and to my fiancé for his patience and love.

TABLE OF CONTENTS

LIST OF TABLES

Page

CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Drought is a common problem in cotton (*Gossypium hirsutum* L.) production. In the relatively moist southeastern Cotton Belt of the USA, significant droughts occurred 8 of 39 years from 1954 to 1993 (North Carolina State University, 2007). Many years in the Texas High Plains have insufficient precipitation to produce a cotton crop (Wishart, 2004). Consequently, irrigation is commonly used in cotton production. Unfortunately, the aquifers that support this irrigation are being depleted. Finally, Fischer et al. (2001) conclude that water deficits will be greater restraints to improved crop productivity in the future because of global warming.

Water was a key determinant of cotton yields in Australia before the current drought. Stiller et al. (2004) in the mid-1990s found that dryland cotton produced only 48% of the yield of irrigated cotton. Furthermore, the cotton fiber of the dryland crop was 4% shorter than the irrigated crop. Pettigrew (2004b) in Mississippi found that drought reduced cotton yields by 25% mainly as a consequence of reducing boll number by 19%. In a related study Pettigrew (2004a) found that the primary effect of drought on above-ground, vegetative growth was a 35% decrease in leaf area index. Krieg and Sung (1986) determined that drought decreased the number of leaves on sympodial branches of cotton. Leaf area of glasshouse-grown cotton also was inhibited when the percentage

---

This thesis follows the style of Crop Science Journal.

of soil available water was less than 51 ± 15% (Rosenthal et al., 1987). Cutler and Rains (1977) concluded that predawn leaf water potentials below -0.5 MPa were accompanied by decreased leaf elongation rate in cotton. McMichael and Hesketh (1982) showed a progress reduction in photosynthetic rate by cotton leaves during drought primarily as a consequence of stomata closure.

Ludlow and Muchow (1990) reviewed the advantages and disadvantages of possible mechanisms of drought resistance in crops. One possibility for enhancing resistance was early maturation to avoid late season drought and minimize total water use. However, the crop may produce early vigorous growth that could limit available water during reproduction, making the crop more vulnerable to early season drought, and leaving available water in soil in good years. An alternate possibility was late maturation to avoid early season drought and making use of all available water in a good year. However, the crop would have a longer time to be exposed to drought and other stresses, and be vulnerable to late season drought.

Indeterminate growth with vegetative and reproductive growth occurring simultaneously could allow reproduction to flush when water availability is good (Ludlow and Muchow, 1990). Unfortunately, indeterminate growth is associated with excessive vegetative compared to reproductive growth, and thus low harvest index. Uneven maturation may limit the effectiveness of a single mechanical harvest.

Deeper roots allow for the greater extraction of water (Ludlow and Muchow, 1990). The additional dry matter distributed to the roots could reduce dry matter partitioning to reproductive growth. It may decrease also the density of roots closer to

the surface. Greater root density may permit the extraction of all available water. Once again, there may be a cost in dry matter to yield. Furthermore, rapid water uptake may deplete water supply before maturity.

Reduced leaf growth and increased rate of leaf aging in response to less water may conserve water (Ludlow and Muchow, 1990). But, it also may decrease photosynthetic capacity and thereby yield potential. Alternately, keeping the stomata open during drought so that photosynthesis can continue as long as possible may promote continued root growth. It could cause plant death by promoting continued water loss.

Finally, Ludlow and Muchow (1990) proposed the selection of plants in a drought environment to let adaptive traits appear through the selection process. However, selection in a poor growing environment producing uniformly low yields may mask genetic differences so that it is difficult to find a high yielding genotype in a good year. In fact, the drought resistant genotype may have a low yield potential.

Several studies have demonstrated that cotton roots are less affected by drought than shoots (Malik et al., 1979, Saab and Sharp,1989, Creelman et al.,1990, McMichael and Quisenberry, 1991, and Ball et al., 1994). Studies have investigated the adaptation of cotton root growth to drought. Pace et al. (1999) examined the seedling shoot and root growth of a long- and a short-season cotton cultivar after a drought of limited duration and a subsequent recovery period. The length of the tap root, but not its dry weight, was greater in the drought-treated plants than the control plants at the end of the drought and recovery periods. The authors concluded that increased tap root length at the expense of

root thickening after drought may permit cotton plants to survive drought by accessing water from deeper in the soil profile. Leaf expansion and root length in cotton, during and after water stress were investigated by Ball et al. (1994) in field and growth chamber studies. Leaf expansion was more sensitive to drought than root elongation. Moreover, root growth initiation increased during recovery. Most of this growth occurred deeper in the soil where more moisture was available. Klepper et al. (1973) measured root development of cotton during drought and found that while death of roots closer to the soil surface increased, new root growth lower in the soil profile increased during drought.

Thus, the studies by Pace et al. (1999), Ball et al. (1994), and Klepper et al. (1973) suggested the importance of greater rooting by cotton plants in response to drought. Root length density, the ratio of root length and soil volume, was found to be important for drought tolerance among eleven peanut (*Arachis hypogaea* L.) genotypes (Songsri et al. 2008). Maiti et al. (2002) concluded that deep rooting was a key element contributing to drought resistance in peanut genotypes. Root characteristics of rice (*Oryza sativa* L.) associated with drought tolerance were greater root length, number of roots, and root density in the 20- to 40-cm soil layer (Ekanayake et al., 1985; Ingram et al., 1995). Greater root growth, rapid water uptake deep in the soil, reduced root death near the soil surface, and rapid root regrowth after rewatering were related to drought tolerance in seven warm season turf grasses (Huang et al., 1997).

McMichael and Quisenberry (1991) identified genetic differences in cotton root growth and branches. Basal et al. (2003) evaluated specific cotton root traits at the

seedling stage for 68 converted race stocks in comparison with two genotypes, TAM 94L-25 (Smith, 2003; PI 631440) and 'Lankart 142,'(PI 542973). They found genetic variation for root length, lateral root number, root fresh weight, lateral root dry weight, and total root dry weight. The authors concluded it is possible to improve seedling-rooting pattern by crossing selected parents.

Basal et al. (2005) evaluated root growth under drought of selected converted race stock, TAM 94L-25, and Lankart 142. Two converted race stocks identified as robust rooting had longer tap root length, higher lateral root number, greater total root dry weight, greater root weight per unit length of tap root, and greater shoot dry weight in both drought and well-watered conditions than two converted race stocks identified as nonrobust. Two cycles of seedling drought resulted in an increase in lateral root number in one robust rooting Converted Race Stock and in TAM 94L-25 and Lankart 142. Moreover, shoot dry weight was highly correlated with total root dry weight and associated with root weight per unit length of taproot. The authors concluded that selected root traits in genetically variable converted race stocks could be useful for enhancing drought tolerance in cotton. This thesis seeks to re-examine and apply this method.

CHAPTER II

MATERIALS AND METHODS

Three generations (C0, C1, and C2) of three genotypes (Deltapine 50 (DPL 50; PI 529566)), TAM 94L-25, and M-8844-0100 (McCarty and Jenkins, 1993; PI 561979) of upland cotton were evaluated in three tests (1, 2, and 3). The C0 cycle represented the parental material that had not been selected previously for seedling drought nor seedling salt tolerance. The C1 generation was the progeny from plants that had undergone at least one cycle of selection for seedling salt and one seedling drought resistance, TAM 94L-25 SST-c1 SDT-c1 and DPL 50 SST-c1 SDT-c1, or three cycles of seedling drought resistance, M-8844-0100 SDT-c3. The C2 generation resulted from one additional selection of C1 plants for seedling drought tolerance noted as SDT-c2 for TAM 94L-25 and DPL 50, and SDT-c4 for M-8844-0100.

To evaluate early vegetative growth, the seeds were planted in 70 x 11 cm tubes filled with 5.6 kg fritted clay (Basal et al. 2005). One hundred eighty tubes were placed and maintained in the greenhouse at the Norman E. Borlaug Center for Southern Crop Improvement, Texas A&M University, College Station, TX. Two seeds were sown per tube and thinned to a single plant. Four replications were evaluated during the experiment.

Each replication consisted of 45 tubes or plants of each generation. All plants in the tubes were watered at one-day intervals. Subsequently, the plants were fertilized with 0.5 mg per plant of Peterson 20-20-20 twice a week.

The genotypes were evaluated when plants ranged from the V3 to the V5 stage of growth (Elsner et al., 1979). Harvested plant tissue was frozen until measurements of fresh weights of shoot (SFW), tap root (TRFW), and lateral roots (LRFW) were recorded. Before drying tap root length (RL) and lateral root numbers (LRN) were measured. Dry weights of shoot (SDW), tap root (TRDW), and lateral roots (LRDW) were measured after 48h in an oven at 90 C.

There were three tests. Test 1 was 63 days from December 2, 2008 to February 3, 2009. Test 2 was 35 days from February 16 to March 23, 2009. Test 3 was 33 days from April 5 to May 8, 2009.

The experiment was performed and analyzed as a split plot of a randomized complete block design with four replications. Main plots consisted of generations, split to genotypes. Main plots were randomized within replications and split plots were randomized within main plots. The experiment was repeated three times, referred to herein as tests. Test 1 was conducted over 63 days, from December 2, 2008 to February 3, 2009. Test 2 required only 35 days from February 16 to March 23, 2009, and Test 3 required 33 days from April 5 to May 8, 2009. The experiment was analyzed using Statistical Analysis System (SAS).

In a companion experiment to evaluate seedling drought resistance and wilting, two seeds from each of three generations and each genotype were sown in 740 containers with four replications and thinned to one plant per container after emergence. Each replication consisted of 20 plants per genotype. All containers were watered to field capacity until the plants reached the first true leaf at which time a cycle of drought

and recovery was initiated. Drought was assessed at two-day intervals by observing apparent wilting at 9 a.m. and 3 p.m. Plants were watered to terminate drought when 75% of the Deltapine 50 C0 plants demonstrated apparent wilting. Percent survival was measured by counting the number of plants that were not wilted at 9 a.m. the next day.

A second drought was imposed immediately recording percent survival at 75% apparent wilting by watering to apparent field capacity. Plants were watered to terminate drought for the second time when 90% of the remaining Deltapine 50 C0 plants were wilted. Percent survival was measured by counting the number of plants that were not wilted at 9 a.m. as described above. The experimental design and statistical analysis was the same as the main experiment.

The objective of this study were [1] to compare early vegetative growth in unselected parents with two selected populations across two cycles for seedling drought for the following traits: taproot length, lateral root number, lateral root fresh and dry weight, and shoot fresh and dry weight, and [2] to compare the unselected parent with two selected populations for seedling drought resistance.

CHAPTER III

RESULTS AND DISCUSSION

Root and Shoot Growth following Selection for Drought/salt Tolerance

Significant variation was found for test, generation, generation x test, genotype, genotype x test, and genotype x generation for root and shoot characteristics (Table 1). Test varied ($p<0.05$) for RL, TRFW, TRDW, LRN, LRFW, LRDW, SFW, and SDW. The first test averaged shorter tap root length, fewer lateral roots, and lower fresh and dry weights for total root, lateral roots, and shoots than test 2 and 3 (Table 2). This first test was conducted in the winter when low light and cool temperatures slowed plant growth. The other two tests, test 2 and 3 were similar, although significant differences were observed for TRFW and LRDW. These tests were conducted in the spring when cotton is normally grown in Central Texas field.

Different environmental conditions such as light, temperature, and water may influence the plant growth and development factors such as the rate of cell wall expansion, and therefore overall plant growth (Taiz and Zeiger, 2006). The optimum temperature requirement for cotton growth and development ranges from 20 to 30 C, with 28 C the optimum for photosynthesis (Burke et al., 1988; Reddy et al., 1991). Greenhouse temperature for test 2 ranged from 26 to 27 C, while the average growth temperature in the greenhouse during the third test ranged from 29 to 35 C. This temperature range during the third test was close to that experienced in many U.S. cotton-producing areas, which frequently ranges from 35 to 40 C (Reddy et al., 1992a).

Similar results were found by Reddy et al. (1992b), where the plants grew faster at 30/22 C day/night cycles and taller at 35/27 C until about 49 d after emergence.

Generation varied ($p<0.05$) for LRN and LRDW (Table 1). A significant interaction of generation x test for LRN prohibits the separation of LRN as a main effect and a significant interaction, also was indicated for TRFW although the main effect was not significant. Averaged across tests, fewer lateral roots resulted in lower LRDW for generation C1 and C2 (Table 3). The significant generation x test appears to have been primarily the result of slow growth in test 1 compared with tests 2 and 3 (Table 4). In test 1 the C2 generation exhibited fewer ($p<0.05$) lateral roots (55) than the C1 generation (62), which had fewer than the C0 generation (68). Similar, yet not significant numbers were observed in test 2 for generations while generations C0 and C2 had fewer lateral roots than the C1 generation in test 3. These results may indicate the complex impact of the environment, especially temperature and radiant energy, on root development since there appears to be no logical explanation of why selecting individual plants for seedling drought/or salt tolerance should result in phenotypes with fewer lateral roots. Although the amount of growth media was no different for every test conducted.

These results contradict those of Pace et al. (1999), who reported that selection for drought tolerance had no impact on LRN in cotton. The results are contrary to the opinion of McMichael et al. (1999), who stated that the drought selection might increase the number of lateral roots in cotton. This opinion was supported by Neumann (2008), who confirmed that selection to drought might increase plant performance. The absolute

differences in these numbers for LRN are probably not biologically meaningful since there is no logical reason that selection for drought or salt tolerance should decrease LRN.

Generations also varied ($p<0.05$) for TRFW across tests, i.e. a significant interaction, although there was not a difference in the average TRFW for generation (Table 1). Data presented in Table 4 indicate that TRFW in generation C1 was higher than in the C0 or C2 generation in the run 3, lower in run 2 and not different in run 1. Again, there is no obvious explanation of these data since there is not a clear pattern across generation.

Significant genotypic differences were found among the genotypes for TRFW, TRDW, LRN, LRFW, LRDW, SFW, and SDW (Table 1). Significant interactions of genotype x run occurred for LRN while genotype x generation interactions were noted for LRN, LRDW, and SDW.

Genotype TAM 94L-25 performed better compared to genotype M-8844-0100 and DPL 50 for TRFW, TRDW, LRN, LRFW, LRDW, SFW, and SDW. TAM 94L-25 averaged higher ($p<0.05$) TRFW, TRDW, LRFW, and SFW compared with M-8844-0100 and DPL 50 (Table 5). These results showed genetic variation for shoot and root characteristics as reported by Basal et al. (2003) in the previous study. On the contrary, shoot parameters were found not to be different under water deficit than well watered conditions from all the genotypes tested during the experiment including TAM 94L-25 (Basal et al. 2005). Furthermore, McMichael and Quisenberry (1991) added that genetic differences did exist in cotton root growth and branches. These results are interesting

since TAM 94L-25 produces mature plants that are shorter and more compact than the other two genotypes in this study (pers. comm., W. Smith). DPL 50 was not different than M-8844-0100, a converted race stock and therefore a genotype that has had essentially no breeding and selection for improved yield or quality potential, in TRFW or TRDW, but DPL 50 did exhibit greater ($p<0.05$) LRFW and SFW than M-8844-0100. These results indicating greater growth rate and biomass for TAM 94L-25 and DPL 50 compared with M-8844-0100 are interesting in that one might logically think that a wild type genotype would produce a plant with more biomass than genotypes that resulted from many years of scientific breeding and selection. That may be the case if the plants had been allowed to grow to maturity but may indicate that breeders have selected for rapid early growth rates and biomass accumulation (pers. comm., W. Smith).

The genotypes varied ($p<0.05$) for LRN within the test as indicated by their interaction component in Table 1. TAM 94L-25 averaged 115 lateral roots in the third test, higher ($p<0.05$) than DPL 50, 101 lateral roots, and M-8844-0100, 100 lateral roots (Table 6). No significant differences were found between these genotypes in test 1, while DPL 50 averaged fewer lateral roots than TAM 94L-25 or M-8844-0100, which were not different, in test 2. The first test that was conducted during the winter months showed the lowest average number of lateral roots compares with tests 2 and 3 when more normal temperatures were encountered.

The interaction between the generation and genotypes was significant for LRN, LRDW, and SDW (Table 1). Table 7 indicated that the unselected M-8844-0100, C0 generation, averaged more ($p<0.05$) lateral roots than DPL 50, yet the lateral roots of M-

8844-0100 were smaller in the generation as indicated by a significantly lower LRDW. In generation C2 TAM 94L-25 exhibited more lateral roots than M-8844-0100 or DPL 50, which were not different in LRN, However TAM 94L-25 exhibited significantly more lateral root biomass. In comparing plants resulting from two cycles of selection for drought or salt tolerance, TAM 94L-25 and M-8844-0100 exhibited the same ($p<0.05$) number of lateral roots and more than DPL 50. However, TAM 94L-25 and DPL 50 exhibited heavier LRDW than M-8844-0100. TAM 94L-25 had numerically higher SDW in all generations, but was not significantly ($p<0.05$) different than DPL 50 in the C0 and C2 generations. These results furthered supported the suggestion that breeders have selected for rapid early plant development.

Seedling Drought Tolerance following Selection for Drought/salt Tolerance

The analysis of variance indicated that the percent wilting and/or recovery from wilt were different ($p<0.05$) among test and generation main effects (Table 8). Seedlings were rated as wilted or not wilted in cycle 1 when 75% of the overall plants were rated as wilted and 90% in cycle 2.

Percent of wilted seedlings did not vary across tests when plants were rated at 75% wilting or 90% wilting but tests did vary in percent recovery (Table 9). Recovery after cycle 1 was higher ($p<0.05$) in test 1 than in test 2, which was higher than test 3. After the second cycle of drought stress, essentially the opposite was found where recovery in test 1 was lower than in test 2 or test 3. Pace et al. (1999) observed that leaf area of drought-treated cotton plants was similar with the untreated plants. This could

lead to the higher rate of recovery on the unselected generation. The higher recovery rate for cycle 2 could be related to photosynthate partitioning being directed to leaf area expansion during the recovery period more in test 2 and 3 compared to test 1.

The premise of this research was that selecting single plants for seedling drought or salt tolerance would result in an increase in such tolerance. That premise was not supported by the data in this experiment where generations of selection had no impact on wilting or recovery (Table 10). No differences were observed in percent wilting across generations for drought cycle 1 and no differences were observed for percent recovery following drought cycle 2. However, and unexpectedly, percent wilting generation C2 in cycle 2 was lower ($p=0.05$) than in generation C0 or C1, which were not different. Generation C2 exhibited the numerically lowest percent recovery following cycle 1 although it was not lower than the C0, or unselected generation. No differences among generations of selection for percent recovery were found following the second cycle of drought stress. On the evaluation of the shoot and root change induced by drought, the drought-treated cotton plants responded faster to wilting by showing lower height, less leaf area, fewer nodes, and lower dry weight at the end of drought treatment (Pace et al. 1999).

CHAPTER IV

CONCLUSIONS

A protocol was developed to evaluate early vegetative growth and seedling of cotton in unselected parents compared with selected populations across cycles for seedling drought resistance. There was no evidence that the selected populations better tolerated drought than the unselected populations. However, TAM 94L-25 had superior root growth than the other genotypes. Genotype TAM 94L-25 averaged higher tap root fresh and dry weight, lateral root fresh weight, and fresh shoot weight.

The percent of wilting and percent recovery of seedling grown in containers were determined through two cycles of drought, one terminated when 75% of the Deltapine 50 C0 seedlings were in apparent wilt and the second cycle subsequent to the first when 90% of the remaining Deltapine 50 C0 plants were in apparent wilt. The cycles did not impact percent wilting, but did impact percent recovery. However, the hypothesis that the selection of a single plant could improve drought and salt tolerance was not supported by the data in the experiment, where selection among the generations had no influence on wilting nor recovery.

REFERENCES

Ball, R. A., D. M. Oosterhuis, and A. Mauromoustakos. 1994. Growth dynamics of the cotton plant during water-deficit stress. Agron. J. 86:788-795.

Basal, H., C. W. Smith., P.M. Thaxton, and J. K. Hemphill. 2005. Seedling drought tolerance in upland cotton. Crop Sci. 45:766-771.

Basal, H., P. Bebeli, C.W. Smith, and P. Thaxton. 2003. Root growth parameters of converted race stocks of upland cotton (*G. hirsutum* L.) and two BC_2F_2 populations. Crop Sci. 43:1983–1988.

Burke, J. J., J. R. Mahan, and J. L. Hatfield. 1988. Crop-specific thermal kinetic windows in relation to wheat and cotton biomass production. Agron. J. 80:553-556.

Creelman, R.A., H.S. Mason, R.J. Bensen, J.S. Boyer, and J.E. Mullet. 1990. Water deficit and abscisic acid cause differential inhibition of shoot versus root growth in soybean seedlings. Plant Physiol. 92:205–214.

Cutler, J.M., and D.W. Rains. 1977. Effects of irrigation history on responses of cotton to subsequent water stress. Crop Sci. 17:329-334.

Ekanayake, I.J., J.C. O'Toole, D.P. Garrity, and T.M. Masajo. 1985. Inheritance of root characteristics and their relations to drought resistance in rice. Crop Sci. 25:927–933.

Elsner, J. E., C. W. Smith, and D. F. Owen. 1979. Uniform stage descriptions in upland cotton. Crop Sci. 19:361-363.

Fischer, G., M. Shah., H. van Velthuizen, and F. O. Nachtergaele. 2001. Global Agro-Ecological Assessment for Agriculture in the 21st Century. Laxenburg, Austria: IIASA and FAO.

Huang, B., R.R. Duncan, and R.N. Carrow. 1997. Drought-resistance mechanisms of seven warm-season turf grasses under surface soil drying: Root aspects. Crop Sci. 37:1863–1869.

Ingram, K.T., R. Rodriguez, S. Sarkarung, and E.B. Yambao. 1995. Germplasm evaluation and improvement for dry seeded rice in drought-prone environments. p. 55–67. *In* K.T. Ingram (ed.) Rainfed Lowland Rice: Agricultural Research for High-risk Environments. Los Banos, Laguna, Philippines.

Klepper, B., H. M. Taylor., M. G. Huck, and E. L. Fiscus. 1973. Water relations and growth of cotton in drying soil. Agron. J. 65:307-310.

Krieg, D.R., and J.F.M. Sung. 1986. Source-sink relationships as affected by water stress during boll development. p. 73-77. *In* J.R. Mauney and J.M. Stewart (ed.) Cotton Physiology. The Cotton Foundation, Memphis, TN.

Ludlow, M.M. and R.C. Muchow. 1990. A critical evaluation of traits for improving crop yields in water-limited environments. Advances in Agronomy 43:107-153.

Maiti, R. K., P. Wesche-Ebeling, A. Nunez-Gonzalez, and E. Sanchez-Arreoa. 2002. Root system and mineral nutrition. In: R. K. Maiti, and P. Wesche-Ebeling, eds. The Peanut (*Arachis hypogaea*) Crop, pp. 125-146. Science Publishers, Inc., Enfield, NH.

Malik, R.S., J.S. Dhankar, and N.C. Turner. 1979. Influence of soil water deficits on root growth of cotton seedlings. Plant Soil 53:109–115.

McCarty, J. C., and Johnie N. Jenkins. 1993. Registration of 79 day-neutral primitive cotton germplasm lines. Crop Sci. 33:351.

McMichael, B. L., D. M. Oosterhuis., J. C. Zak, and C. A. Beyrouty. 1999. Growth and development of root system, *In* J. M. Stewart et al. (ed.) Cotton Physiology. Book II. National Cotton Council, Memphis, TN.

McMichael, B.L., and J.E. Quisenberry. 1991. Genetic variation for root-shoot relationship among cotton germplasm. Environ. Exp. Bot. 31:461–470.

McMichael, B. L. and J. D. Hesketh. 1982. Field investigation of the response of cotton to water deficits. Field Crops Sci. 5:319-333.

Neumann, Peter. M. 2008. Coping mechanisms for crop plants in drought-prone environments. Ann. Bot. 101:901-907.

North Carolina State University Cooperative Extension. 2007. Drought management for cotton production. Electronic Publication Number DRO-17. North Carolina State University. Raleigh, NC.

Pace, P. F., H. T. Cralle., S. H. El-Halawany., J. T. Cothren, and S. A. Senseman. 1999. Drought-induced changes in shoot and root growth of young cotton plants. J. Cotton. Sci. 3:183-187.

Pettigrew, W. T. 2004a. Physiological consequences of moisture deficit stress in cotton. Crop Sci. 44:1265-1272.

Pettigrew, W. T. 2004b. Moisture deficit effects on cotton lint yield, yield components, and boll distribution. Agron. J. 96:377-383.

Reddy, K. R., H. F. Hodges, and V. R. Reddy. 1992a. Temperature effects on cotton fruit retention. Agron. J. 84:26-30.

Reddy, K. R., V. R. Reddy, and H. F. Hodges. 1992b. Temperature effects on early season cotton growth and development. Agron. J. 84:229-237.

Reddy, V. R., D. N. Baker, and H. F. Hodges. 1991. Temperature effect on cotton canopy growth, photosynthesis, and respiration. Agron. J. 83:699-704.

Rosenthal, W. D., G. F. Arkin., P. J. Shouse, and W. R. Jordan. 1987. Water deficit effects on transpiration and leaf growth. Agron. J. 79:1019-1026.

Saab, I.N., and R.E. Sharp. 1989. Non-hydraulic signals from maize roots in drying soil: Inhibition of leaf elongation but not stomatal conductance. Planta 179:466–474.

Smith. Wayne. 2003. Registration of TAM 94 L-25 and TAM 94 J-3 germplasm lines of upland cotton with improved fiber length. Crop. Sci. 43:741-742.

Songsri, P., S. Jagloy., N. Vorasoot., C. Akkasaeng., A. Patanothai, and C. C. Holbrook. 2008. Root distribution of drought-resistant peanut genotypes in response to drought. J. Agron. & Crop Sci. 194:92-103.

Stiller, W. N., P. E. Reid, and G. A. Constable. 2004. Maturity and leaf shape as traits influencing cotton cultivar adaptation to dryland conditions. Agron. J. 96:656-664.

Taiz, L, and E. Zeiger. 2006. Plant Physiology. Fourth Edition. Sinauer Association, Sunderland, MA.

Wishart, D.J. 2004.Encyclopedia of the Great Plains. U of Neb. Press. Lincoln, NB.

APPENDIX

Table 1. Mean squares of root and shoot characteristic across generation C0, C1, and C2 with genotypes M-8844-0100, DPL.
50, and TAM 94L-25 in test 1, 2, and 3 when grown under greenhouse culture at College Station, TX in 2008-2009.

		Mean square			
Source		RL†	TRFW	TRDW	LRN
Test	2	46740.340**	2.520**	0.865**	25126.718**
Error a	9	792.327	0.030	0.012	877.902
Generation	2	37.452	0.003	0.014	557.145*
Generation x Test	4	77.988	0.028*	0.008	258.265*
Error b	18	54.664	0.008	0.010	118.795
Genotype	2	22.019	0.118**	0.058**	580.803*
Genotype x Test	4	78.660	0.025	0.005	570.701*
Generation x Genotype	4	140.095	0.048	0.012	562.085**
Generation x Genotype x Test	8	258.482	0.017	0.007	127.117
Error c	54	110.496	0.016	0.011	170.814

* significant at P=0.05 level.

** significant at P=0.01 level.

† RL, root length; TRFW, taproot fresh weight; TRDW, taproot dry weight; and LRN, lateral root number.

Table 1. continued.

Source	df	Mean square			
		LRFW†	LRDW	SFW	SDW
Test	2	3.009**	4.756**	13.110 **	1.311 **
Error a	9	0.298	0.038	1.699	0.077
Generation	2	0.148	0.072**	0.065	0.020
Generation x Test	4	0.183	0.008	0.672	0.029
Error b	18	0.157	0.013	0.341	0.016
Genotype	2	2.007*	0.256 **	6.007 **	0.424 **
Genotype x Test	4	0.168	0.055	0.554	0.034
Generation x Genotype	4	0.535	0.265 **	0.666	0.128 **
Generation x Genotype x Test	8	0.248	0.017	0.378	0.027
Error c	54	0.160	0.023	0.445	0.040

* significant at P=0.05 level.

** significant at P=0.01 level.

† LRFW, lateral root fresh weight; LRDW, lateral root dry weight; SFW, shoot fresh weight; and SDW, shoot dry weight.

Table 2. Root and shoot characteristics of tests 1, 2, and 3 when grown in tubes under greenhouse culture at College Station, TX in 2008-2009.

Test	RL§	TRFW	TRDW	LRN	LRFW	LRDW	SFW	SDW
	- cm -	---------- g ----------		- number -	---------- g ----------			
1	24.56 b†	0.30 c	0.11 b	61 b	1.21 b	0.19 c	3.45 b	0.68 b
2	84.46 a	0.71 b	0.36 a	109 a	1.55 a	0.74 b	4.37 a	1.05 a
3	89.21 a	0.80 a	0.40 a	105 a	1.78 a	0.88 a	4.58 a	1.17 a

† Means within columns followed by the same lower case letter are not different at *k=100* according to Waller-Duncan LSD.

§ RL, root length; TRFW, taproot fresh weight; TRDW, taproot dry weight; LRN, lateral root number; LRFW, lateral root fresh weight; LRDW, lateral root dry weight; SFW, shoot fresh weight; and SDW, shoot dry weight.

Table 3. Root and shoot characteristics of generations C0, C1, and C2 when grown in tubes under greenhouse culture at College Station, TX in 2008-2009.

Generation	LRN§	LRDW
	- number -	- g -
C0	95 a†	0.65 a
C1	93 a	0.60 b
C2	88 b	0.56 b

† Means within columns followed by the same lower case letter are not different at *k=100* according to Waller-Duncan LSD.
§ LRN, lateral root number and LRDW, lateral root dry weight.

Table 4. Interaction among test 1, 2, and 3 with generations C0, C1, and C2 when grown in tubes under greenhouse culture at College Station, TX in 2008-2009.

Test	Generation	TRFW§	LRN
		- g -	- number -
1	C0	0.32 e†	68 d
	C1	0.31 e	62 e
	C2	0.31 e	55 f
2	C0	0.73 c	112 a
	C1	0.67 d	107 abc
	C2	0.74 c	107 abc
3	C0	0.75 c	105 c
	C1	0.86 a	109 b
	C2	0.81 b	104 c

† Means within columns followed by the same lower case letter are not different at *k=100* according to Waller-Duncan LSD.
§ TRFW, taproot fresh weight and LRN, lateral root number.

Table 5. Root and shoot characteristics of genotypes M-8844-0100, DPL 50, and TAM 94L-25 when grown in tubes under greenhouse culture at College Station, TX in 2008-2009.

Genotype	TRFW§	TRDW	LRN	LRFW	LRDW	SFW	SDW
	g		- number -	g			
M-8844-0100	0.57 b†	0.26 b	91 b	1.27 c	0.51 c	3.70 c	0.77 b
DPL 50	0.58 b	0.27 b	88 b	1.53 b	0.61 b	4.18 b	0.91 a
TAM 94L-25	0.67 a	0.34 a	96 a	1.74 a	0.68 a	4.51 a	0.99 a

† Means within columns followed by the same lower case letter are not different at *k=100* according to Waller-Duncan LSD.

§ TRFW, taproot fresh weight; TRDW, taproot dry weight; LRN, lateral root number; LRFW, lateral root fresh weight; LRDW, lateral root dry weight; SFW, shoot fresh weight; and SDW, shoot dry weight.

Table 6. Interaction among tests 1, 2, and 3 with genotypes M-8844-0100, DPL 50, and TAM 94L-25 when grown in tubes under greenhouse culture at College Station, TX in 2008-2009.

Test	Genotype	LRN§
		number
1	M-8844-0100	63 e†
	DPL 50	64 e
	TAM 94L-25	59 e
2	M-8844-0100	113 b
	DPL 50	99 cd
	TAM 94L-25	112 b
3	M-8844-0100	100 c
	DPL 50	101 c
	TAM 94L-25	115 a

† Means within columns followed by the same lower case letter are not different at *k=100* according to Waller-Duncan LSD.
§ LRN, lateral root number.

Table 7. Interaction among generations C0, C1, and C2 with genotypes M-8844-0100, DPL 50, and TAM 94L-25 when grown in tubes under greenhouse culture at College Station, TX in 2008-2009.

		LRN§	LRDW	SDW
Generation	Genotype	- number -	- g -	- g -
C0	M-8844-0100	102 a†	0.59 f	0.82 ef
	DPL 50	93 cd	0.68 bc	0.93 bc
	TAM 94L-25	98 ab	0.78 a	0.91 cd
C1	M-8844-0100	96 abc	0.60 ef	0.90 cde
	DPL 50	92 de	0.64 bcd	0.86 cde
	TAM 94L-25	98 ab	0.68 bc	1.04 a
C2	M-8844-0100	83 f	0.44 g	0.67 g
	DPL 50	87 ef	0.63 de	0.95 ab
	TAM 94L-25	102 a	0.69 b	1.04 a

† Means within columns followed by the same lower case letter are not different at *k=100* according to Waller-Duncan LSD.
§ LRN, lateral root number; LRDW, lateral root dry weight; and SDW, shoot dry weight.

Table 8. Mean squares of percent wilting and percent recovery across generation C0, C1, and C2 with genotypes M-8844-0100, DPL 50, and TAM 94L-25 after two cycles of drought when grown in greenhouse culture at College Station, TX in 2008-2009.

		Mean square			
		Wilting		Recovery	
Source	df	Cycle 1	Cycle 2	Cycle 1	Cycle 2
Test	2	144.444	172.143	23150.232 **	3247.09 **
Error a	9	335.802	407.282	916.82	411.686
Generation	2	243.028	568.751 *	234.028 *	15.191
Generation x Test	4	215.972	223.076	321.759	554.885
Error b	8	143.904	123.143	236.728	336.499
Genotype	2	89.583	19.639	9.954	48.191
Genotype x Test	4	116.32	122.899	49.19	137.985
Generation x Genotype	4	49.653	94.701	54.398	53.244
Generation x Genotype x Test	8	168.576	64.81	117.071	180.522
Error c	54	131.019	151.664	175.231	231.06

* significant at P=0.05 level.
** significant at P=0.01 level.

Table 9. Percent wilting and percent recovery for test 1, 2, and 3 after two cycles of drought when grown under greenhouse culture at College Station, TX in 2008-2009.

	Wilting		Recovery	
Test	Cycle 1	Cycle 2	Cycle 1	Cycle 2
	percent			
1	80.00	91.23	67.64 a†	12.83 b
2	76.11	86.90	35.28 b	31.52 a
3	78.89	89.66	17.64 c	25.15 a

† Means within columns followed by the same lower case letter are not different at *k=100* according to Waller-Duncan LSD.

Table 10. Percent wilting and percent recovery for generations C0, C1, and C2 after two cycles of drought when grown in greenhouse culture at College Station, TX in 2008-2009.

	Wilting		Recovery	
Generation	Cycle 1	Cycle 2	Cycle 1	Cycle 2
	percent			
C0	77.22	92.68 a†	42.22 b	22.57
C1	76.53	90.21 a	43.06 a	23.08
C2	81.25	84.90 b	35.28 b	23.86

† Means within columns followed by the same lower case letter are not different at *k=100* according to Waller-Duncan LSD.

VITA

Name:	Elvira Sari Dewi
Address:	c/o Dr. Harry Cralle Texas A&M University Department of Soil and Crop Sciences 2474 TAMUS College Station, TX 77843-2474
Email Address:	elvira@tamu.edu; elvira.fp@gmail.com
Education:	B.S., Agronomy, Syiah Kuala University, Indonesia 2002 M.S., Agronomy, Texas A&M University, 2009